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Virtual Kinship Networks: Exploring Social Networks from an Agent-Based Model

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Abstract

This paper analyzes the structure of virtual kinship networks formed by an agent-based model that was originally designed to explore the relationships among kin networks, residence rules, settlement size, and the movement of exchange goods.Following simple rules, agents in the model are born, die, find mates, establish post-marital residence. Agents then exchange goods (which are conceptualized as pottery vessels) among close kin dispersed through a linear system of villages. Each run of the model produces a network that unites most agents, but each agent also has a personal network of close kin. Previous analysis of model output has focused on variation in the number of virtual pottery vessels obtained by agents, and on data averaged over large numbers of model runs, with only minimal analysis of the networks produced. But variation in network structure must underlie the variation in exchange success seen in the model runs. This paper focuses on the virtual networks produced by the model, including examining variation in measures of centrality and degree distribution, as well as variation in path length from one end of the system to the other. The data exploration reported here indicates that centrality is important, but centrality alone is not a good predictor of success in exchange. Agents who obtain large numbers of vessels typically are connected to producers directly or through one or two intermediate links, and also tend to have relatively high centrality in the network.

Keywords: agent-based modeling, exchange, social networks

Introduction

This paper explores the structure of virtual kinship networks formed by an agent-based model that was originally designed to investigate the relationships among kin networks, residence rules, settlement size, and the movement of exchange goods in a simulated exchange network. The model was inspired by archaeological ceramic distributions where contemporary and adjacent households acquired quite different amounts of imported ceramics. It is often difficult to get large enough samples that can be clearly associated with individual archaeological households, but wherever ceramic assemblages from individual households, or small groups of a few households, can be separated, it is common to find that the relative abundances of trade ware pottery vary much more than can be accounted for by sampling error (e.g., Allison 2019; Allison 2008; Ossa 2013; Watts and Ossa 2016).

Variation in the relative abundance of non-local ceramics may reflect differences in household wealth and status, although the variation occurs among households in small-scale farming societies where there is little evidence for strong differences in prestige or wealth. Access to goods from distant sources may be better for some households than others for other reasons, however. Specifically, several recent attempts to model exchange have emphasized the importance of small-world networks (e.g., Brughmans and Poblome 2016a; Brughmans and Poblome 2016b; Ibañez et al. 2015; Ortega et al. 2014). The model analyzed here was developed to test the intuition that, under certain conditions, exchange networks formed through kinship would tend to be small-world networks in which some individuals were more successful in acquiring exchange goods.

Previous analysis of the model results (Allison 2020) shows that it is generally true that trade along kinship lines results in large differences in how successful agents are in acquiring trade ware vessels, with the variation being largest when the size of settlement size is smallest. This variation in exchange success must be due to random variation in the size and specific composition of the virtual kin networks formed by the model, but the details of those networks have not previously been examined.

The purpose of this paper is to begin to examine the networks formed in the simulation and how individual's positions in those networks affect their success in acquiring vessels through exchange. These networks are not created to have any specific form, but rather they emerge through agents following simple rules of kinship, marriage and residence. Exchange is then channeled through kinship links. Because the networks emerge in part through stochastic effects, each run of the model creates a different network, which makes analysis complicated and generalizations difficult. To simplify, I will focus on a few questions. First, how does network topology vary with the size of settlements and overall population (which are correlated because the number of settlements is constant)? Specifically, are there differences in the distributions of degree centrality, betweenness centrality, or the path lengths between settlements as settlement size varies. For these broad questions about the structure of networks, I will use 50 runs of the model, ten each with initial settlement size population set to 100, 200, 300, 400, and 500 agents (the actual population of settlements varies stochastically as agents are born and die according to specific probabilistic rules).

A second set of questions focuses in on how centrality of agents or path length to ceramic producers affects success in acquiring vessels in exchange. If exchange success is in fact a result of agents being well-positioned in a small-world network, then path length to producers should be positively correlated with the number of vessels acquired, but network centrality should not be as important. For some analyses relevant to these question I use the full complement of 50 model runs, but I also will focus in on the specific kin networks of a few agents in two runs of the model, one with initial village size set to 100, the other with it set to 500.

Brief Description of the Model

The model is implemented in NetLogo 6.0 and is available for download at https://github.com/jallison7/kintrade-model. Allison (2020) describes the model more completely; here I present a brief summary to help readers make sense of the analyses that follow.

The model is inspired by the archaeological case studies described in Allison (2019; Allison 2008), but is not specifically based on any real world situation. It creates settlements ("villages") evenly spaced in a line from left to right (in NetLogo's "world" display)

Initial Village Size	Total No of Agents at End	Village Size at End	Degree Centrality		Betweenness * 100		Path Length	
		mean	mean	median	mean	median	mean	median
100	6116	76.5	5.6	3	0.8	0.006	2.9	3
200	13701	171.3	5.7	3	0.4	0.009	3.4	3
300	20256	253.2	5.6	3	0.3	0.010	3.5	3
400	28418	355.2	5.7	3	0.2	0.005	3.4	3
500	36004	450.1	5.6	3	0.2	0.004	3.8	4

Table I: Statistics from 50 total runs of the model

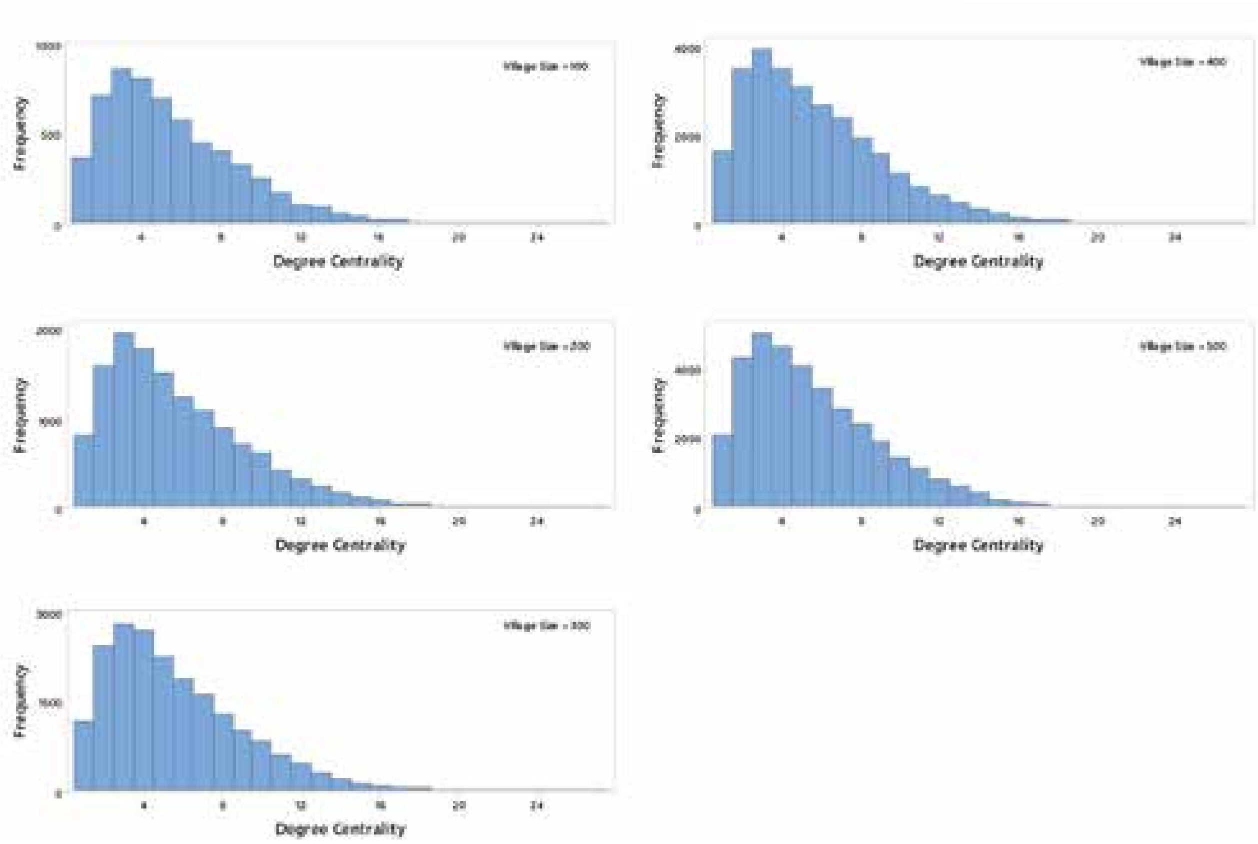

Figure 1. Degree distribution for networks created with different initial village sizes.

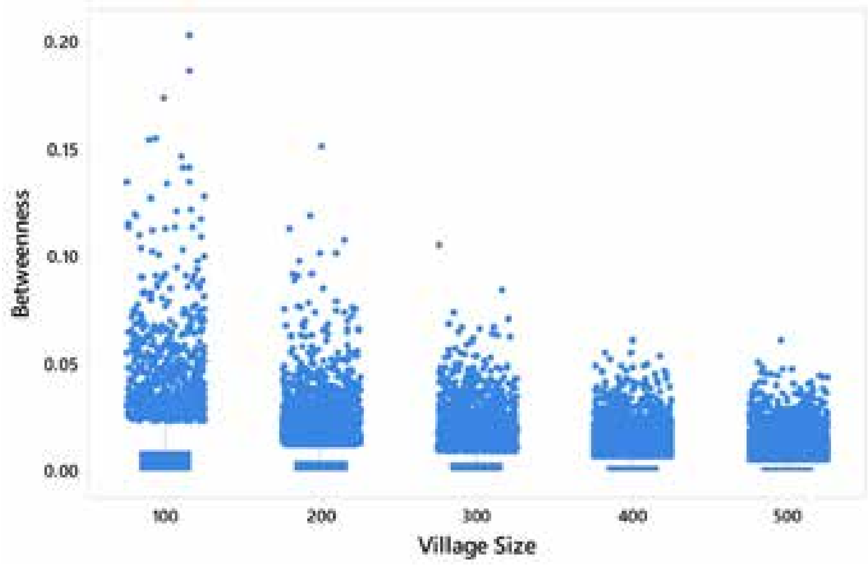

Figure 2. Box plots of betweenness for agents in the networks created by the model at different initial village sizes.

within an abstract, featureless landscape. The number of villages can vary, but all the runs of the model reported here use eight villages (the [otherwise arbitrary] choice to use a linear arrangement of eight villages is an homage to Wright and Zeder's [1977] pioneering model of exchange, which was one of the first agent-based models in archaeology). The villages are numbered left to right, and the two villages at the left side of the system (i.e., Villages 1 and 2) are defined as producing villages.

The initial mean population size of the villages is set before each run. The actual number of village residents is random; the model randomly chooses the number of male and female agents to create in each

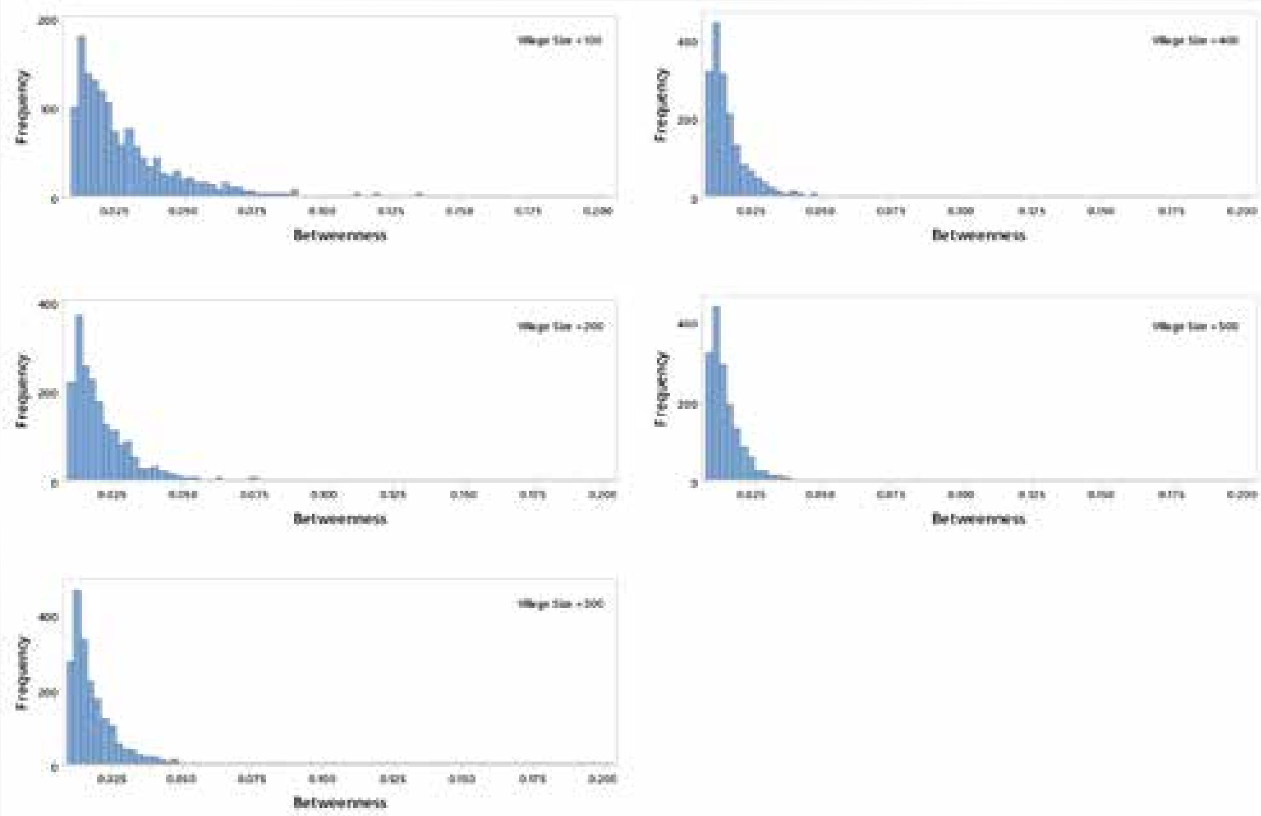

Figure 3. Histograms of normalized betweenness values for networks created at different village sizes, with betweenness values below 0.01 excluded.

village from a Poisson distribution (with a mean = ½ the mean initial village size). Agents in this initial group are randomly assigned ages, then seek spouses, with age restrictions. The system is matrilocal with a preference for endogamy (i.e., agents marry within their home village if possible); if no spouse is available in the home village, men move to their spouse's village. The simulation then runs for 100 years (each NetLogo "tick" is conceptually one year) while agents have children, marry, and die according to specific rules. The model links spouses, parents and children, and siblings. Agents are also linked directly to their spouses parents and siblings. After 100 years, the simulation will have created a network that indirectly links most or all of the agents in the model, and agents will have their own networks of first and second order links. But because birth, death, marriage, and reproduction are all subject to stochastic affects, some agents will be directly or closely connected to many other agents, while others have few close connections.

After the simulation has run for 100 years to allow the network to emerge, female agents in the producing village begin producing pots, and the pots are then traded, with all transactions occurring between directly linked individuals. Several variables in the model were held constant in the model runs reported here. These include the number of vessels produced annually by each producer (5), the number of vessels an individual must possess before they are willing to give one to a relative (2), and the number of vessels agents can acquire in a year before they stop trying to get more (5). The length of the period during which exchange takes place was also held constant (at 50 years), although it also is potentially variable. Agents continue to be born, age, marry, reproduce, and die throughout the period of exchange. Birth and death probabilities are also variable in the model but fixed in the runs reported here. The probability that any agent over the age of 16 will die in a given year was fixed at .05. Birth probability, or the probability that a female between the age of 16 and 40 will have a child in a given year was set at .017 (since agents under 16 cannot die in the model, this value really reflects the probability that a female agent will have a child that survives to adulthood rather than a raw birth rate).

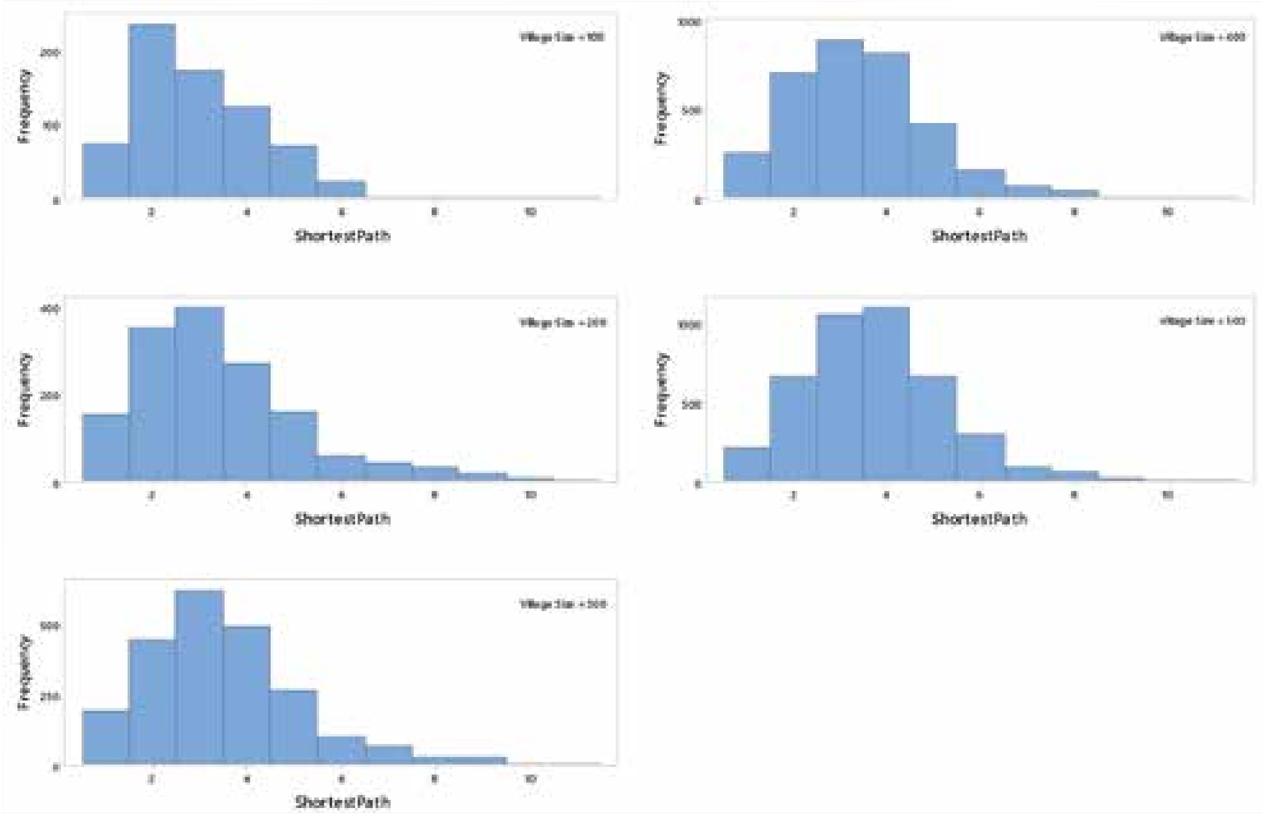

Figure 4. Distributions of shortest path lengths from Village 8 agents to agents in the producer villages (Villages 1 and 2).

These settings lead to relatively stable populations, although, as the first two columns of Table 1 show, population tends to decline slightly throughout the duration of the simulation. The actual sizes of villages vary somewhat, but by the end of the 150 year run, mean village population is about 87 percent of the initial village size.

Analysis, Part 1: The Effect of Settlement Size on Centrality and Path Length

Settlement size, which correlates to total population size, has almost no effect on the distribution of degree centrality. Agents have a mean of 5.6 or 5.7 direct links, regardless of the size of the total network, and the median is 5.0 for every village size setting (Table 1). The distributions of degree centrality are all skewed (Figure 1), with individual agents having more than 20 direct links, but the distributions are virtually identical regardless of settlement size.

Betweenness centrality varies more with initial settlement size, although the distributions are so skewed that it is difficult to graph them clearly. The boxplots in Figure 2 show that almost all the agents at every settlement size have very small betweenness values, but there are large numbers of outliers. Because of the large number of tiny values, it is difficult to scale histograms of the full distributions to show much except a large mode in each histogram for the bin that includes zero. Figure 3 excludes a total of 95,708 agents that have normalized betweenness centrality less than 0.01; excluding those values makes it much easier to see that the range of values is higher when the settlement (and total) populations are smaller. In other words, when populations are smaller, it is possible for some agents to be more central to the network than they can be when settlement size, and the size of the total network, are larger. This is reflected in the mean values for betweenness, which are always small but decrease steadily as settlement size increases, while the median values are much tinier, with fluctuations that are likely just due to sampling error.

Path lengths also vary with population size, although again the effects are subtle. Figure 4 shows the shortest paths for agents in Village 8 (furthest from the producers) to any agent in one of the two producing villages. At each village size, most agents

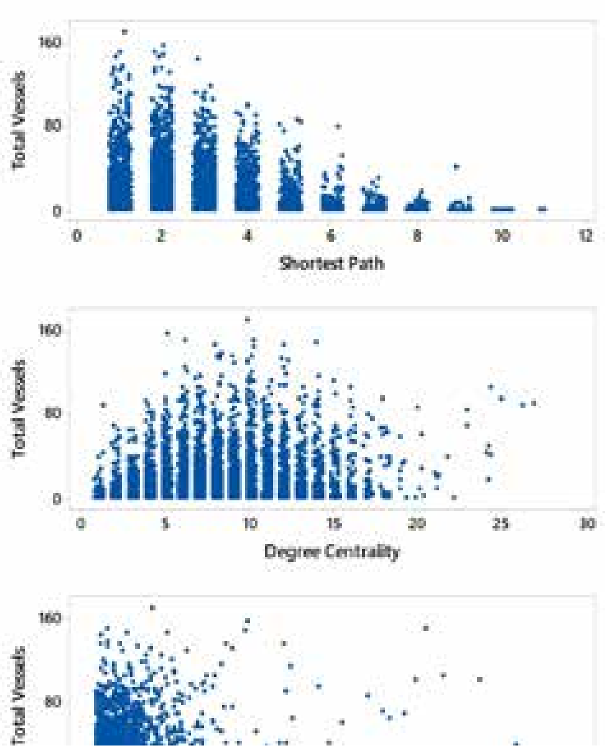

Figure 5. Plots of the relationship between total vessels acquired and path length, degree centrality, and betweenness for Village 8 agents across all 50 runs of the simulation.

in Village 8 are connected to someone in the producing village by four or fewer links, and the mdian is three for every village size except 500 (Table 1). The mean path length increases from 2.9 to 3.8, however, and 44 percent of the Village 8 agents are directly connected to someone in a producing village (i.e., path length = 1) when village size is 100, compared to only 21 percent when village size is set to 500.

In general, then, there are some slight differences in the characteristics of networks created by the simulation as population sizes increase. The degree distributions of the networks vary little with village size. At every population size, the simulation creates networks within which most agents have three or fewer direct links, but a few agents have many more. At every initial village size setting, most agents have similar, quite small values for betweenness, indicating that most agents are not very central to the network, although the range of values is larger when the network is smaller. Path lengths across the virtual landscape also vary with population size; when settlement size is small, the model creates networks in which many agents at the far end of the system (in Village 8) are linked to the producing village directly or with relatively few links. At larger population sizes, average path lengths increase, although a few Village 8 agents are still connected to producers directly.

Analysis, Part 2: Path Length, Centrality, and Success in Acquiring Vessels

Path length to the producing villages does have a large effect on the number of vessels acquired by agents. The upper graph in Figure 5 shows that relationship for all agents in Village 8, across all 50 runs of the simulation (a total of more than 12,000 agents). Total vessels, as shown in Figure 5, is the sum of vessels in possession of agents at the end of a simulation run, and vessels that they acquired earlier but gave away before the end of the run. Although the relationship is visually striking, the correlation is actually quite small (r2 = .09) because so many agents acquire only small numbers of vessels, even when they are connected to one of the producing villages through few links. This may mean there are confounding variables (age is one likely factor, since older individuals have more opportunities to acquire vessels). But, clearly, some individuals with short paths to producing villages are able to acquire large numbers of vessels, which individuals with longer path lengths are not able to do so.

Neither degree centrality nor betweenness seems to have a strong or consistent relationship with pots acquired, however (Figure 5), except that agents with high centrality scores tend to have at least moderate numbers of vessels. But the individuals with the largest numbers of vessels have low to moderate centrality in the network. The correlations with total vessels are actually higher than for path length (.16 for degree centrality and .22 for betweenness) but are still low.

The overall relationships among these variables are suggestive but ambiguous. Having a short path to a producing village seems to be necessary, but not sufficient, for agents to acquire large numbers of vessels. And agents that are highly central in the network almost always have some success at acquiring vessels. But the patterns shown in Figure 5 indicate that other factors must be important as well.

Figure 6 shows the relationship between total vessels and path length and between degree centrality and betweenness for Village 8 residents in two runs of the simulation. In the top row of the figure, the ini-

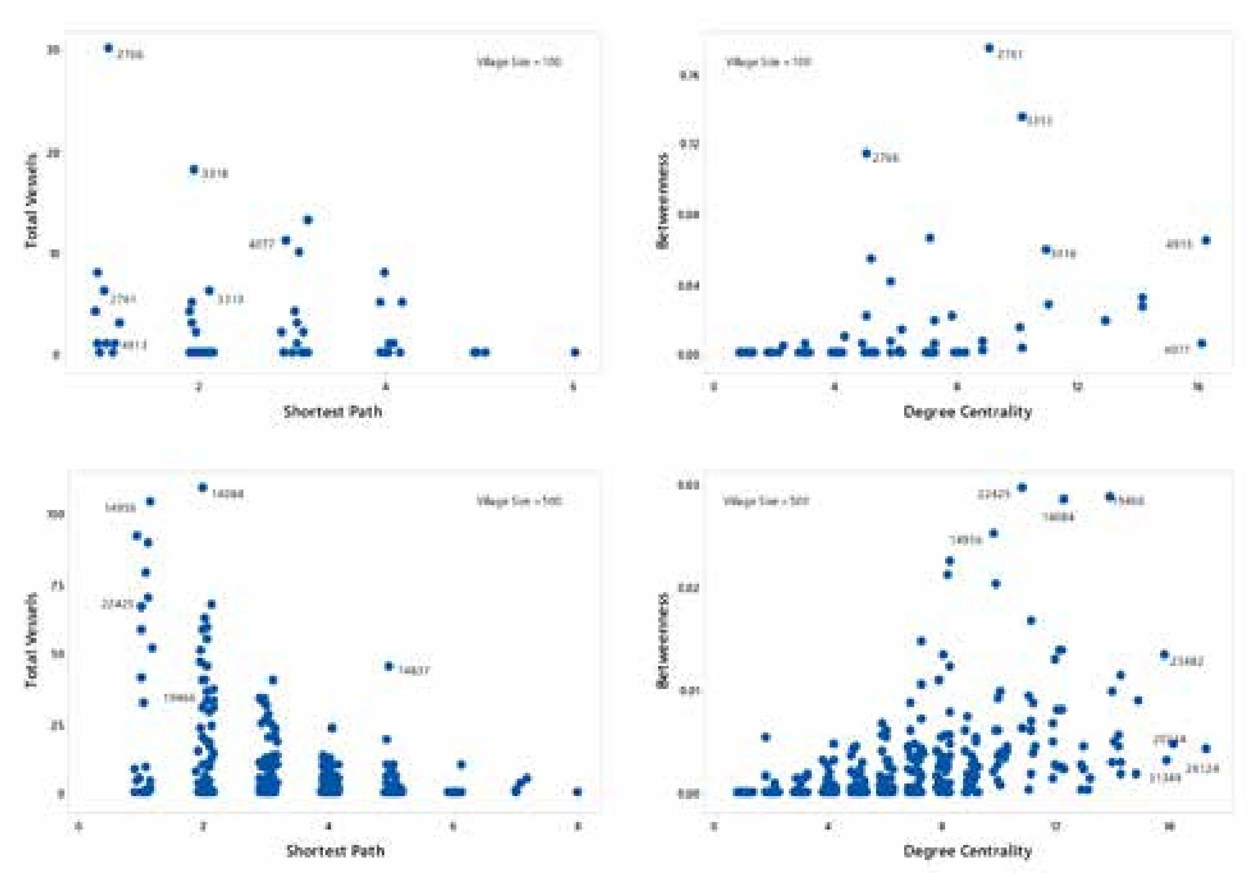

Figure 6. Trench H, Terrestrial Laser Scan 3D model

tial village size was 100, in the bottom row it was 500. Aside from the differences in the number of data points resulting from the different population sizes, the graphs from the two runs are similar. The agents who acquire the most vessels always have direct connections to a producing village or a relatively short path, and agents with relatively high betweenness values always have moderate to high degree centrality, although the reverse is less true. Many agents with relatively high degree centrality have low betweenness values.

A few individual agents are labeled in Figure 6 that have large numbers of vessels acquired, high centrality, or both. A closer examination of the details of those agents and their closest connections provides insight into the nature of the networks that emerge in the simulation and how agents' situations within the networks affect their success in obtaining vessels through exchange.

In the top half of Figure 6, showing Village 8 residents from one run of the model with initial village size set to 100, most of the labeled agents are closely connected to each other and have overlapping networks of close connections (Figure 7).

Agent 2766, a 59 year-old male who has acquired more vessels than any other Village 8 resident, was born in Village 7 but married into Village 8. Agent 2761 is his spouse, through whom he connects to a large group of Village 8 agents (plus others). They both have direct connections to agents in the producing villages. Agent 2766 is directly connected to Agent 4404, a female who lives in Village 1. At the end of the simulation Agent 2766 only owned 5 vessels (2 of which were produced by 4404), but he had traded away 25 others. He has relatively high betweenness (0.11) and moderate degree centrality 5, as shown in the upper right graph in Figure 7.

Agent 2761, 2766's spouse, is also 59 years old. At the end of the simulation she only owned one vessel and had traded away five. She stands out as having the highest betweenness of any Village 8 resident (0.17) and relatively high degree centrality (9). She is directly connected to Agent 3665, a male who lives in Village 2.

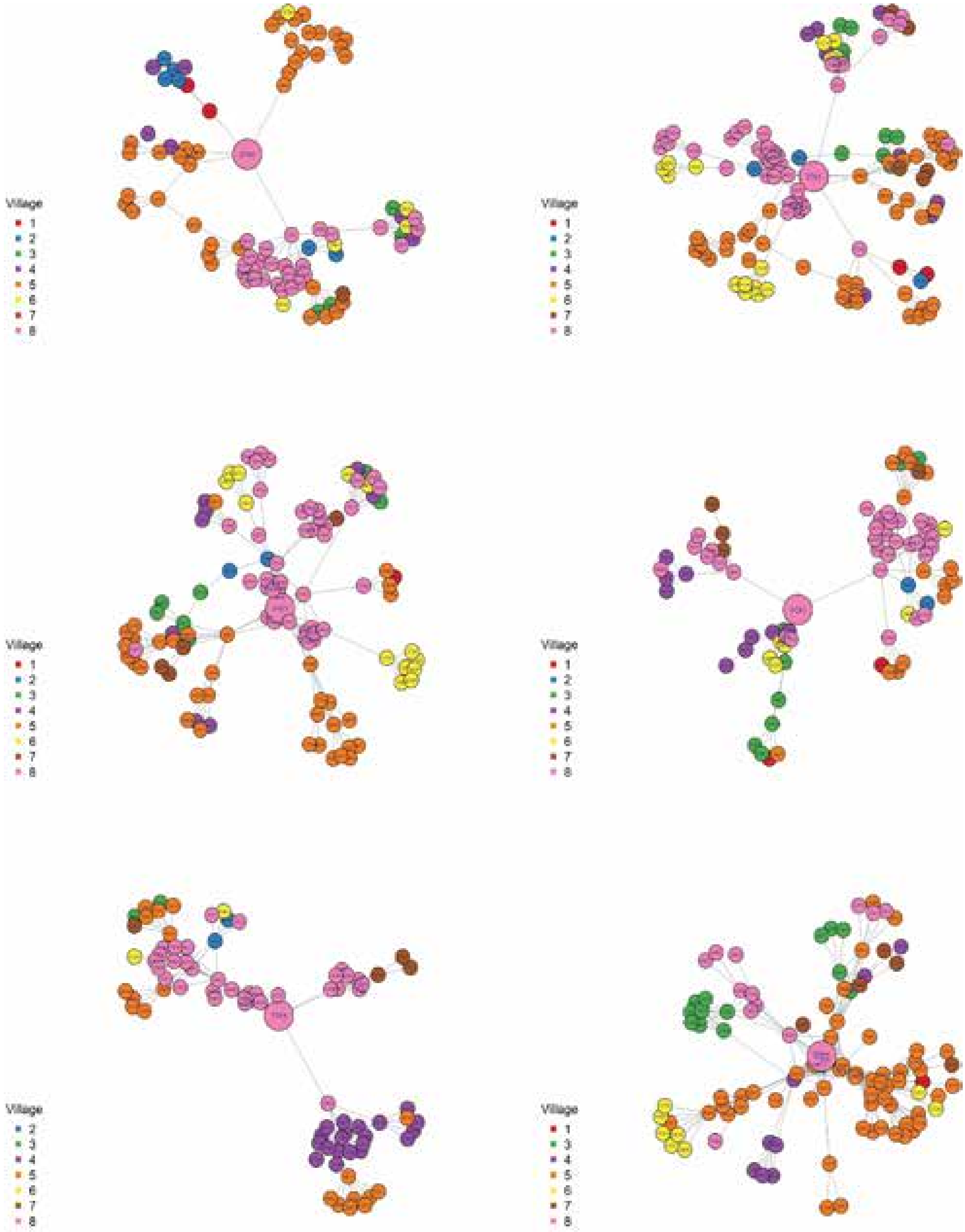

Figure 7. Network graphs of the closest connections for specific agents labeled in the upper half of Figure 6.

4913 is a 24 year-old male, the son of agent 2761 from a previous marriage (his father is deceased). He is highly central in the network, at least in terms of degree centrality (16), and he shares the direct con-

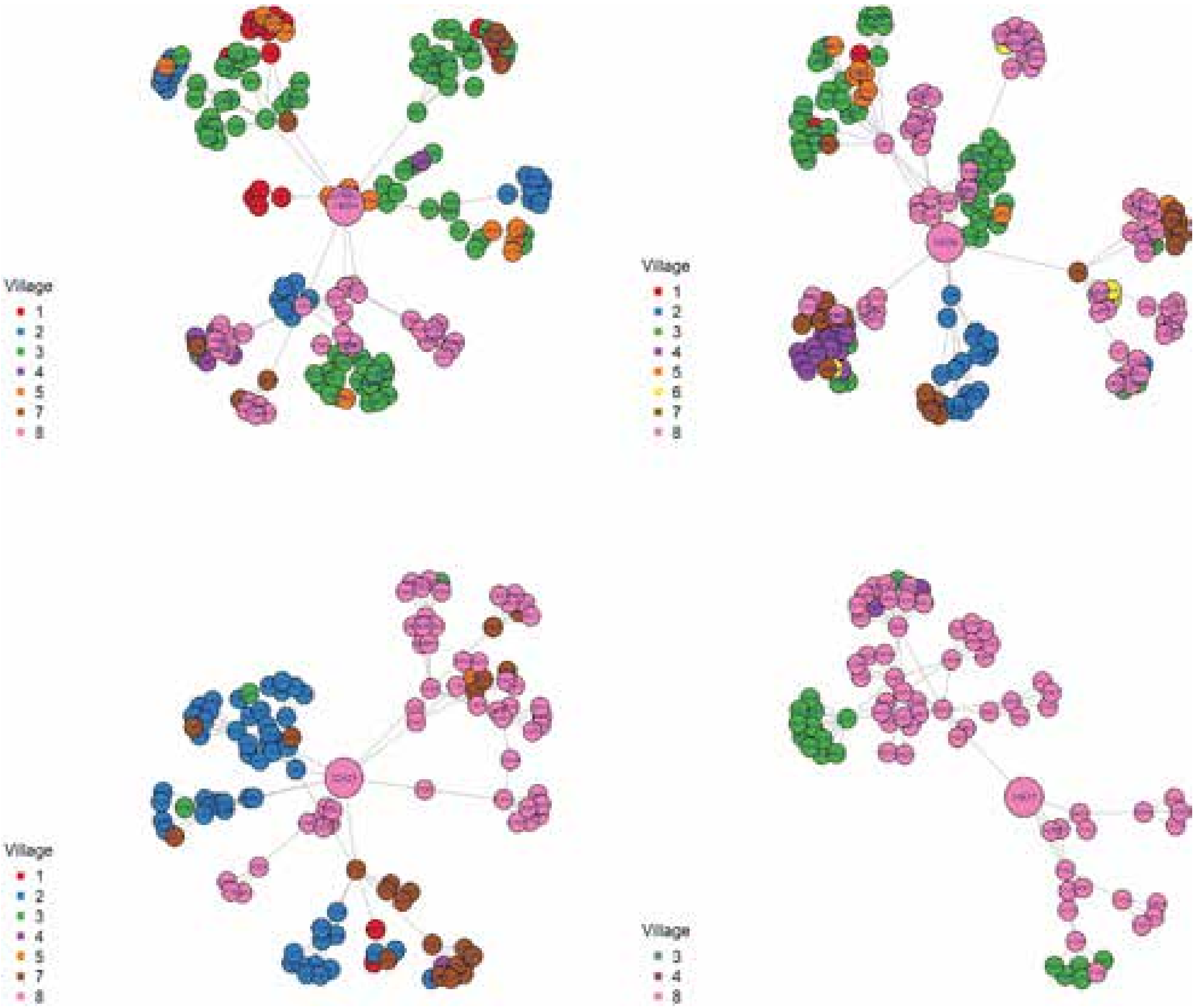

Figure 8. Network graphs of the closest connections for four of the agents labeled in the lower half of Figure 6.

nection with his mother to Agent 3665 in Village 2. This probably means that means that 2761's deceased spouse, and father of 4913 married into Village 8 from Village 2, although information about agents who die before the end of the model run is not recorded, so the specifics of that connection cannot be verified. Despite Agent 4913's high centrality and direct connection to a producing village, he has only acquired one vessel. That may be due in part to his relatively young age.

Agent 3313 is a 48 year old female, who has high betweenness and degree centrality (10). Her close connections overlap substantially with Agent 2761, who is her sister, and she connects indirectly to Agent 3665 in Village 2 through her sister. At the end of the simulation she only owned 1 vessel, but had traded away 5.

3316 is also a 48 year old female, who owns only one vessel but has acquired and traded away 17. Her closest connection is also to Agent 3665, through Agent 4913 who is married to her daughter. It is not clear why she was more successful in obtaining vessels than other agents with largely overlapping networks and equally short or shorter paths to the producers.

Most of the Village 8 agents in this run of the simulation who have high centrality or large numbers of vessels are thus closely connected to each other. Agent 4077 is an exception. He is a 37 year old male who was born in Village 5. At the end of the simulation he owned six vessels and had traded away five others. He is tied for the highest degree centrality in the village (16), but has very low betweenness (.006), and is two links away from the

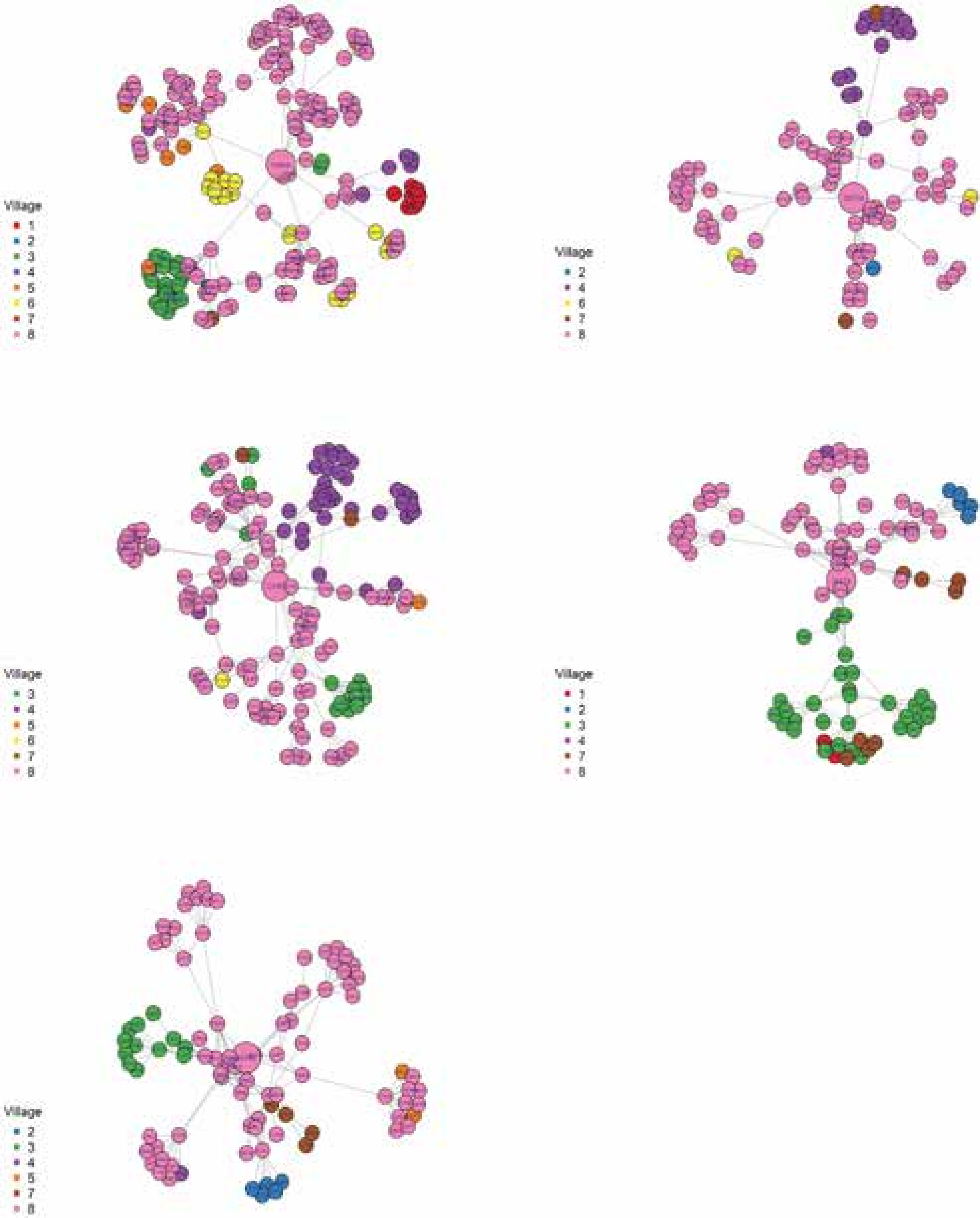

Figure 9. Network graphs of the closest connections for five agents labeled in the lower half of Figure 6.

producing village. His closest connection in a producing village is Agent 5097, a male who was born in Village 6 but married into Village 1. The connection goes through two Village 5 residents, Agent 5094 who is his sister, and Agent 5095, sister in-law to 5094, who is married to Agent 4863, 5097's brother. Again it is not clear why Agent 4077 was relatively successful at obtaining vessels, although

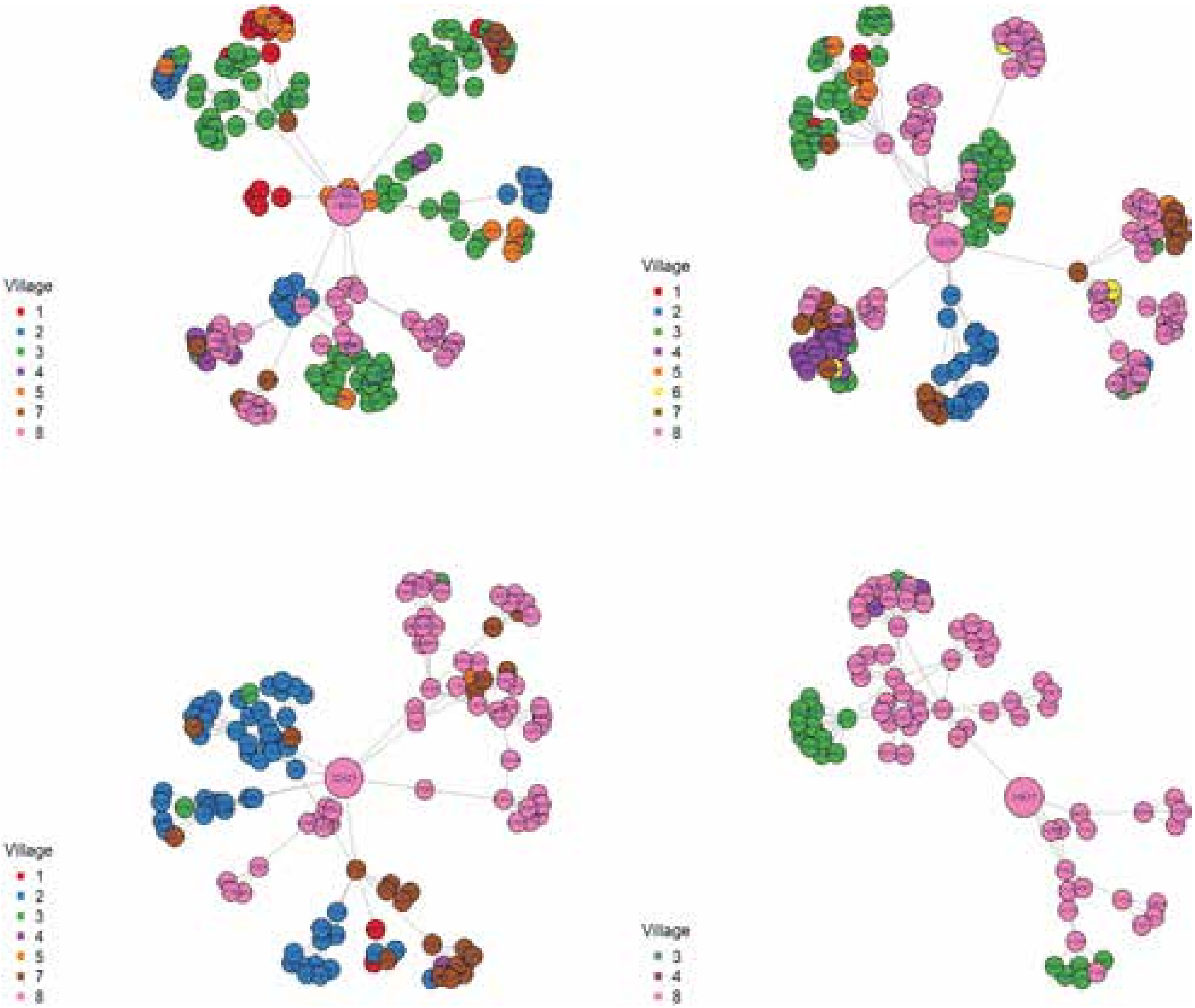

Figure 10. NGraphs showing the relationships between centrality measures and total pots acquired for Village 8 agents from one run of the simulation with initial village size set to 500. The upper row graphs the relationships for agents with short path lengths to producer villages; the bottom row shows the weaker relationship for agents with longer path lengths.

it probably is due to his large number of direct connections, many of which are to agents in Village 5 (closer to the producers, which means that on average agents there have more vessels to exchange than Village 8 residents).

With village size set to 500, the model creates many more agents, and there are more producers to make vessels. That means more vessels make it to Village 8, and some agents acquire large numbers of them, although most agents there have none or relatively few. As Figure 6 shows, the agents with large numbers of vessels are either directly connected to someone in a producing village, or connected through only one intermediary.

Agent 14084, a 60 year-old male, has the largest total number of vessels (109, 25 of which he still owned at the end of the simulation), and his spouse, Agent 14956 has the second largest (she only owned four at the end of the simulation, but had previously acquired and traded away 100). Agent 14956 is 52 years old, and is directly connected to Agent 17296, a female who lives in Village 2 (Figure 8). Both Agent 14084 and 14956 have high betweenness and degree centrality, which probably accounts, in part, for their success in acquiring vessels.

Agent 22425 has the highest betweenness of any Village 8 resident, and relatively high degree centrality as well. He is a 39 year-old male who was born in Village 2 and is directly connected to four different Village 2 residents, including his mother and sister. The combination of short path length to producers and his centrality in the network enabled success in acquiring vessels; he owned 12 vessels at the end of the simulation and had given away 58 more.

Agent 14837 stands out for having had relatively good success at acquiring vessels despite not having any close connections to producing villages (Figure 6). She is 53 years old and has acquired 45 vessels, although she only still owned one at the end of the simulation. Not only does she have a relatively long path length to the producers, she is not particularly central to the network; she has degree centrality of five, but her betweenness is only .002 (which puts her low on the graph in Figure 6 where there are so many points it is impossible to add a label). Although she is five nodes away from any agents in the producing villages, her path length to Village 3 is only two (through her husband, Agent 20318, to Agent 22707; Figure 8), which may account for her success in the exchange system.

Agent 19466 is a 46 year-old male who has high degree centrality (14) and betweenness (.03), but only moderate success at acquiring vessels compared to other agents with a path length of 2 (Figure 6). As Figure 9 shows, almost all of his direct connections are with other agents in Village 8, and the high betweenness appears to be the result of being on the shortest path between groups of Village 8 residents, which is unlikely to be an advantage in the exchange network. He does have a short path to a group of Village 1 residents through Agent 24327, who is married to his sister, and this apparently allowed him to have some success in exchange.

Four other agents are labeled in the bottom right graph of Figure 6 (Agents 20734, 23482, 26124, and 31349). These are all agents with very high degree centrality (Figure 9), and low or moderate betweenness. Despite their centrality, none of them were particularly successful in obtaining vessels. Three of them (20734, 26124, and 31349) have path lengths of three to producer villages, and 20 or fewer total vessels acquired. Agent 23482 has slightly higher betweenness, but a path length of 4, and was only able to acquire 12 vessels. All four of those agents have many close connections to other Village 8 residents (Figure 9), and relatively fewer connections to agents in distant villages compared to the networks of the agents shown in Figure 8 who were more successful in acquiring vessels.

Taken together, the examination of these individual agents and their networks suggests that both path length to producer villages and centrality are important in determining who is able to acquire vessels in the virtual exchange system. A short path to producers is important, but many individuals with direct connections to producing villages do not obtain many vessels. As figure 10 shows, there is a correlation between network centrality and total pots acquired, but the correlation is stronger for path lengths of one or two (r2 = .56 for betweenness, .31 for degree centrality) than for longer path lengths (r2 = .28 for betweenness, .11 for degree centrality).

Conclusion

The agent-based model that produced the networks analyzed here provides a rich source of data about the relationships between network structure and success in exchange. But the relationships are complex, and getting a clear picture of what is going on in the network produced by one run of the simulation is difficult. Generalizing is even more difficult. But a few points are clear. First, population size and the size of settlements has little effect on the degree distributions of the networks produced. The simulation always creates networks with highly skewed degree distributions where most agents have few direct links, but a few agents have many more. Betweenness is also not strongly affected by differences in population size, although the range of normalized betweenness values seems to increase slightly when population is small.

Increasing population size has a stronger affect on the number of agents with short path lengths from Village 8 to the producing villages. When population is small, a higher proportion of agents have connections that span the length of the virtual exchange system. This is because when settlement size is small, more agents are unable to find spouses in their home village, despite the built-in preference for village endogamy. This leads to increased movement between villages, which is the mechanism that accounts for long-distance connections in the model.

Path length to producers and centrality are both important in leading to success in acquiring vessels through exchange, but the relationships are complex.

The individuals who obtain the most vessels usually have short path lengths to producing villages and above average centrality.

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